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Physics of quantum well and quantum dot infrared photodetectors

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Abstract.   We review the recent studies of physical effects in quantum well and quantum dot infrared photodetectors utilizing intersubband transitions.

Introduction

Electron and hole processes in semiconductor superlattices have been the topic of extensive experimental and theoretical studies for almost three decades. This is due to a variety of interesting physical effects in such systems and their device applications. A great deal of attention has also been paid to the electron (hole) phenomena in multiple quantum well (QW) structures with a weak coupling between QWs. These QW structures are used in infrared photodetectors utilizing intersubband transitions [1]. QW infrared photodetectors (QWIPs) on the base of AlGaAs/GaAs and other heterostructures utilizing intersubband absorption have been successfully implemented for wavelengths in the range $4-28$ μm [1, 2]. The application of large QWIP arrays in infrared cameras is in the developing stage (see, for example [3]). The basic physics of QWIPs has been well documented [1, 4, 5]. However, as shown recently, the spectrum of physical effects arisen in QWIPs under different conditions is wider than expected and their in-depth understanding and utilization need further thorough investigation. Despite QWIPs have been successful in different applications, the replacement of QWs by arrays of quantum dots (QDs) in infrared photodetectors (QDIPs) is very promising. QDIPs have been predicted to have some important advantages over QWIPs [6] such as the sensitivity to normally incident radiation, lower dark current, and higher photoelectric gain. Different InAs/GaAs, InGaAs/GaAs, InGaAs/InGaP, and Si/Ge QDIPs have been recently fabricated and experimentally studied by several groups [7–16]. In this paper we review the recent results concerning physical aspects of QWIP and QDIP operation focusing primarily on the electron transport, capture, and injection phenomena in such devices.

1. Principles of QWIP and QDIP operation

The QWIP structure consists of a number of doped QWs separated by relatively thick undoped layers forming the inter-well barriers. Such a QW structure is clad by doped layers playing roles of the emitter and collector contacts. In QDIPs, arrays of QDs are used instead of QWs. Generally, the principles of operation of QWIPs and QDIPs are similar. Actually, their operation principles are also similar to those of the photodetectors utilizing impurity excitation. The excitation (thermal- and photoexcitation) of electrons from the bound states in QWs or QDs ensures the occurrence of mobile electrons propagating over the continuum states. The energies of intersubband bound-to-bound and bound-to-continuum transitions are in the mid- or far infrared ranges of spectrum. Under applied voltage, the generation of mobile electrons results in the electron current across the QW or QD structure. An

additional ionization of QWs or QDs due to the increase of the excitation rate (say, because of the increase in the flux of infrared photons) leads to the redistribution of the electric potential in the structure. This, in turn, gives rise to the increase in the electric field near the emitter contact. The latter leads to strengthening of the electron injection from the emitter contact. The total electron current is determined by both the excited and injected electrons. In the steady-state conditions, the concentration of electrons in QWs (QDs) and, hence, the space charge in the structure, are maintained by the balance between the electron excitation and the capture of previously excited and injected electrons. The type of the injection from the emitter contact to the QWIP (QDIP) active region depends on their band alignment. The emitter layer in QWIPs is primarily made of a material with narrower energy gap than that of the inter-well barriers, so that the injection of electrons into the QWIP active region is associated with the tunneling through the barrier separating the emitter contact layer and the extreme (first) QW [1]. Contrary, in QDIPs the emitter layer is usually made of the same material as the material of the barriers between QDs [7–16]. Because of this, the electron injection in such QDIPs is due to thermionic injection over the barrier created by the charged QD layer (enriched by electrons) adjacent to the emitter contact [6].

2. Heating of electrons and their capture

As the capture processes in QWIPs and QDIPs play an important role in the performance of these devices, the dependence of the capture rate on the local value of the electric field can be a significant factor. Apart from the effect of electric field on the photoelectric gain, it essentially influences the spatial distribution of the self-consistent electric field in the device active region. There are two mechanisms of the effect of electric field. First, the local electric field influences the probability of such elementary processes as the unbound-bound phonon-assisted electron transitions. Secondly, the electric field in the QWIP (or QDIP) active region usually leads to a significant heating of electrons. As a result, the fraction of low energy electrons which can be captured, say, with the emission of optical phonons drastically decreases with increasing electric field. Taking into account that the direct field effect is not so strong in the range of normally used electric fields, the electron heating can be the most significant one. The results of ensemble Monte Carlo particle study of the heating mechanism yield nearly exponential dependence of the electron capture rate on the electric field [17] which is consistent with the experimental data [18, 19]. A strong electric-field dependence of the capture rate can be one of the most important factors determining the QWIP current-voltage characteristics [20] both in dark conditions and under illumination. Residual donors in the barriers and nonuniform distribution of donors in QWs (associated with features of the growth processes and leading to an asymmetric form of the QWs [21]) can markedly complicate the electron heating and, hence, the electric-field dependence of the capture rate [22].

3. Contact and space charge effects

Early models of QWIPs with multiple QWs are based on the assumption that the electric-field distribution in the active region is uniform [23, 24]. Such simplified models assume that the emitter contact is perfectly injecting [23], i.e., it injects as many electrons as needed by the QW structure. Hence, the injected current density should be that which ensures the required concentration of mobile electrons and, consequently, the required rate of electron capture into QWs to compensate the excitation of electrons from the QWs. A real emitter contact yields such an injected current density if the contact electric field has a proper value which can significantly differ from the average electric field in the active region. An

appropriate electric field at the emitter contact is created by a space charge in the structure arisen due to the difference in the concentrations of bound electrons and donors. The space charge in donor doped QW (and QD) structures can be either positive or negative. The existence of a space charge in the active region results, in general, in the nonuniformity of the electric field. It has been demonstrated using numerical simulations [25–27], that in QWIPs with a large number of QWs, the region of nonuniform electric field can be relatively narrow and located near the injecting contact. However, in QWIPs in which the local electric field weakly affects the excitation of electrons from the QWs and their capture into the QWs (in particular, due to a strong nonlocality of the electron heating), the electric-field distributions can be essentially nonuniform but fairly smooth with the scale of nonuniformity comparable to the active region thickness [28]. Thus, strongly nonuniform distributions, like distributions with high electric field domain near the emitter, are associated with relatively strong dependences of the electron excitation and capture rates upon the local value of the electric field. As a result, the electric-field distribution in a QWIP and, consequently, some its characteristics are determined by both the emitter contact parameters and the field dependences of the rates. However, the overall characteristics of QWIPs with a large number of QWs can be rather insensitive to the emitter contact parameters in a wide range of applied voltage [28, 29]. In contrast, the contact and space charge effects in QWIPs with a moderate number of QWs can be essential [28] (see also [20]) giving some flexibility for the optimization of such devices. In addition, properties of the emitter contact can manifest themselves in nonlinear effects in QWIPs, for example, at a high power of incident infrared radiation. Some of the features associated with the contact and space charge effects can reveal in QDIPs as well [30].

4.   Recharging instability and periodic domains

As usually reasoned (see above), the electric-field distributions in QWIPs are monotonic. They correspond to rather smooth distributions of the potential. A novel effect in multiple QW structures with uncoupled QWs under infrared excitation — the formation of periodic and near periodic electric-field and charge domains — has been predicted recently using an ensemble Monte Carlo particle method [31, 32]. This effect is associated with the excitation of the QW recharging waves. The origin of the recharging waves, predicted for the first time in compensated semiconductors with deep traps [33, 34], is associated with the exis-tence of two groups of electrons (mobile and bound) and the electron exchange between the groups. It is natural that the periodicity of the QW locations leaves its imprint. As shown previously [35, 36], the transient photocurrent in QWIPs includes a slow component, which is attributed to the recharging processes. More detailed study using ensemble Monte Carlo particle method which takes into account nonequilibrium and nonlocal effects reveals ad-ditional features of the QWIP response to step-like pulses of infrared radiation including oscillatory transients [32, 37]. The development of the recharging instability leads either to the establishment of periodic or near periodic electric-field and charge structures with the period equal to twice the QW structure period or to pronged chaotic pulsations. The formation of periodic or near periodic electric-field and charge structures can significantly influence the operation of QWIPs, particularly, at high power excitation level. A study of such a self-organization in QWIPs is important in view of their application for photomix-ing and heterodyne detection [38]. As QWIP high frequency operation is primarily limited by electron transit-time [39, 40] and velocity overshoot effects [41, 42], a strong periodic nonuniformity of the electric field pronouncedly affecting the electron dynamics can be very significant factor. The transition from smooth monotonic electric-field distributions

to periodic one's occurs with increasing intensity of infrared radiation when the photoexcitation rate overcomes the rate of thermoexcitation [43]. This effect can be responsible for low power nonlinearities in QWIPs observed experimentally [27].

5. Application of QWIPs and QDIPs in pixelless infrared imaging devices

Recently, the concept of integrated QWIP and light emitting diode (LED) has been proposed [44] and realized [45] to convert long wavelength infrared radiation into short wavelength one. Further development of this idea has led to the concept of QWIP-LED pixelless imaging device [46, 47]. In this device, long wavelength infrared radiation absorbed in the QWIP due to intersubband transitions generates mobile electrons. A fraction of them is injected into the device LED part causing short wavelength infrared radiation from the active layer where the electrons injected from the QWIP recombine with holes. If the incident radiation is nonuniform (input long wavelength infrared image), the electron current injected into the LED and, hence, the intensity of output short wavelength infrared radiation are nonuniform as well. Thus, the spatial distribution of the output radiation repeats the form of the distribution of the photocurrent in the QWIP which, in turn, repeats the spatial distribution of incoming radiation. Physical effects both in the QWIP and LED parts of such imagers limiting their characteristics were analyzed in Refs. [47, 48]. It has been shown that when the number of QWs in the QWIP part of the QWIP-LED imager is sufficiently large, the electron spreading in this part is insignificant. As a consequence, the main factors limiting the efficiency of up-conversion and the quality of the image conversion are associated with the processes in the LED part of the imager, namely with low external LED efficiency (due to the total internal reflection of a significant portion of the generated short wavelength infrared photons) and with the photon recycling effect in the latter [48] (increasing the external efficiency but leading to an additional smearing of the image [49]). The replacement of a QWIP by a QDIP in such a QDIP-LED pixelless imaging device [30] can be beneficial for the enhancement of its performance.

References

[1] B. F. Levine, *J. Appl. Phys.* **74**, R1 (1993).

[2] A. G. U. Perera, W. Z. Shen, S. G. Matsik *et al.*, *Appl. Phys. Lett.* **72**, 1596 (1998).

[3] S. D. Gunapala, S. V. Bandara, J. K. Liu *et al.*, *IEEE Trans. ED* **47**, 326 (2000).

[4] H. C. Liu, *Long Wavelength Infrared Photodetectors*, ed. M. Razeghi (Gordon and Breach, Amsterdam, 1996), p. 1.

[5] K. K. Choi, *The Physics of Quantum Well Infrared Photodetectors* (World Scientific, Singapure, 1997).

[6] V. Ryzhii, *Semicond. Sci. Technol.* **11**, 759 (1996).

[7] K. W. Berryman, S. A. Lyon and M. Segev, *Appl. Phys. Lett.* **70**, 1861 (1997).

[8] J. Phillips, K. Kamath and P. Bhattacharya, *Appl. Phys. Lett.* **72**, 2020 (1998).

[9] S. Kim, H. Mohseni, M. Erdtmann *et al.*, *Appl. Phys. Lett.* **73**, 963 (1998).

[10] D. Pan, E. Towe and S. Kennerly, *Appl. Phys. Lett.* **73**, 1937 (1998).

[11] S. Maimon, E. Finkman, G. Bahir *et al.*, *Appl. Phys. Lett.* **73**, 2003 (1998).

[12] S. J. Xu, S. J. Chua, T. Mei *et al.*, *Appl. Phys. Lett.* **73**, 3153 (1998).

[13] N. Horiguchi, T. Futatsugi, Y. Nakata *et al.*, *Jpn. J. Appl. Phys.* **38**, 2559 (1999).

[14] J. Phillips, P. Bhattacharya, S. W. Kennerly *et al.*, *IEEE J. QE* **35**, 936 (1999).

[15] D. Pan, E. Towe and S. Kennerly, *Appl. Phys. Lett.* **75**, 2719 (1999).

[16] C. Miesner, O. Rothig, K. Bruner and G. Abstreiter *Appl. Phys. Lett.* **76**, 1428 (2000).

[17] M. Ryzhii and V. Ryzhii, *Jpn. J. Appl. Phys.* **38**, 5922 (1999).

[18] E. Rosencher, B. Vinter, F. Luc *et al.*, *IEEE Trans. QE* **35**, 936 (1999).

[19] E. Rosencher, F. Luc, P. Bois *et al.*, *Appl. Phys. Lett.* **63**, 3312 (1993).

[20] V. Ryzhii and H. C. Liu, *Jpn. J. Appl. Phys.* **38**, 5815 (1999).

[21] H. C. Liu, Z. R. Wasilewski, M. Buchanan and H. Chu, *Appl. Phys. Lett.* **63**, 761 (1993).

[22] M. Ryzhii, V. Ryzhii and M. Willander, *Jpn. J. Appl. Phys.* **38**, 2559 (1999).

[23] H. C. Liu, *Appl. Phys. Lett.* **60**, 1507 (1992).

[24] S. R. Andrews and B. A. Miller, *J. Appl. Phys.* **70**, 993 (1991).

[25] M. Ershov, V. Ryzhii and C. Hamaguchi, *Appl. Phys. Lett.* **67**, 3147 (1995).

[26] L. Thibaudeau, P. Bois and J. Y. Duboz, *J. Appl. Phys.* **79**, 446 (1996).

[27] A. Sa'ar, C. Mermelstein, H. Schneider et al., *IEEE Photonics Technol. Lett.* **10**, 1470 (1998).

[28] V. Ryzhii, *J. Appl. Phys.* **81**, 6442 (1997).

[29] H. C. Liu, L. Li, M. Buchanan and Z. R. Wasilewski, *J. Appl. Phys.* **82**, 889 (1997).

[30] V. Ryzhii and I. Khmyrova, *Proc. SPIE* (to be published).

[31] M. Ryzhii, V. Ryzhii, R. Suris and C. Hamaguchi, *Jpn. J. Appl. Phys.* **38**, L1388 (1999).

[32] M. Ryzhii, V. Ryzhii, R. Suris and C. Hamaguchi, *Phys. Rev. B* **61**, 2742 (2000).

[33] R. F. Kazarinov, R. A. Suris and B. I. Fuks, *Fiz. Tech. Poluprov.* **7**, 149 (1973).

[34] R. A. Suris and B. I. Fuks, *Fiz. Tech. Poluprov.* **7**, 1556 (1973).

[35] M. Ershov, C. Hamaguchi and V. Ryzhii, *Jpn. J. Appl. Phys.* **35**, 1395 (1996).

[36] S. Ehret, H. Schneider, C. Schonbein *et al.*, *Appl. Phys. Lett.* **69**, 931 (1996).

[37] M. Ryzhii and V. Ryzhii, *IEEE Trans. ED* (to be published).

[38] E. R. Brown and K. A. McIntosh, in *Thin Films*, eds M. H. Francombe and J. L. Vossen (Academic, New York, 1998), Vol. 23, p. 173.

[39] C. G. Bethea, B. F. Levine, G. Hasnain, J. Walker and R. J. Malik, *J. Appl. Phys.* **66**, 963 (1989).

[40] V. Ryzhii, I. Khmyrova and M. Ryzhii, *IEEE Trans. ED* **45**, 293 (1998).

[41] M. Ryzhii and V. Ryzhii, *Appl. Phys. Lett.* **72**, 842 (1998).

[42] M. Ryzhii, V. Ryzhii and Willander, *J. Appl. Phys.* **84**, 3403 (1998).

[43] I. Khmyrova, M. Ryzhii, V. Ryzhii, R. Suris and C. Hamaguchi, *Jpn. J. Appl. Phys.* **38**, 6654 (1999).

[44] V. Ryzhii, M. Ershov, M. Ryzhii and I. Khmyrova, *Jpn. J. Appl. Phys.* **34**, L38 (1995).

[45] H. C. Liu, J. Li, Z. R. Wasilewski and M. Buchanan, *Electron. Lett.* **31**, 832 (1995).

[46] H. C. Liu, L. B. Allard, Z. R. Wasilewski and M. Buchanan, *Electron. Lett.* **33**, 379, (1997).

[47] V. Ryzhii, H. C. Liu, I.Khmyrova and M. Ryzhii, *IEEE J. QE* **33**, 1527 (1997).

[48] V. Ryzhii, I.Khmyrova and Ph. Bois, *IEEE J. QE*, **35** 1693 (1999).

[49] N. Tsutsui, I.Khmyrova, V. Ryzhii and T. Ikegami (unpublished).